INFORMATION COPY

EVALUATION OF THE POTENTIAL
OF
CLOSE RANGE PHOTOGRAMMETRY
FOR
TUNNEL MAPPING AT THE
NEVADA TEST SITE

Technical Report
Prepared as part of Contract# 6-9530-03737

For

George M. Fairer
U.S. Geological Survey
Denver, Colorado

By

Sean Curry
VEXCEL Corporporation
Boulder, Colorado

September, 1986

VEXCEL TR 08-04-86

DRAFT

TABLE OF CONTENTS

	ABSTRACT	1
1.0	Introduction	2
2.0	Why Photogrammetry	5
3.0	Photogrammetric Image Acquisition	6
4.0	Photogrammetric Data Acquisition	20
5.0	Data Base Design & Implementation	33
6.0	Proposals	39
7.0	Conclusions	

Appendix A - Camera Information

Appendix B - DSR-11

Appendix C - CRISP Information

Appendix D - INGRES

Appendix E - Intergraph

DRAFT

ABSTRACT

VEXCEL Corporation was contracted by the US Geological Survey to investigate the potential applications of close range photogrammetry to the mapping of underground drifts in the Exploratory Shaft Project. During a visit to the site, stereo photographs were taken, and survey control points measured. The sample photographs were measured on a Kern DSR-11 Analytical Plotter using the CRISP software package. A number of recommendations were made concerning photographic procedures, survey methods, and photograph measurement techniques. Data base design principles were reviewed, and a number of potential close range mapping systems proposed.

1.0 INTRODUCTION

DRAFT

The Exploratory Shaft Project (ESP) is a part of the Nevada Nuclear Waste Storage Investigations program. The ESP must record the position and orientation of geologic data in nearly two miles of underground drifts in a nuclear waste repository site. Two mapping methods are available for these purposes:

1) Traditional direct underground methods, which tend to be personnel-intensive and time consumptive;

2) Indirect mapping using close-range terrestrial photogrammetry. This method has the potential to reduce time and cost, and has many side benefits.

Photogrammetry may be defined as

> "the art, science, and technology of obtaining reliable information about physical objects and the environment through processes of recording, measuring, and interpreting photographic images and patterns of electromagnetic radiant energy and other phenomena."[1]

Typically, photogrammetry is used for the compilation of topographic maps from stereo aerial photographs. However, it has its origins in precise terrestrial surveys used for the documentation of projects, construction including mountain railroads and transalpine tunnels in Europe at the turn of the century. There are also many modern examples of the application of photogrammetry to geological problems. Not many have been on the scale of the ESP, and the potential size of this project requires a careful study of procedures.

---

1. Manual of Photogrammetry, pp 1, American Society of Photogrammetry, Falls Church, VA, 1980.

DRAFT

VEXCEL Corporation was contracted by the U.S. Geological Survey to evaluate the application of close-range photogrammetry to the tunnel mapping project, and to propose methods for developing and testing an operational system for underground mapping. VEXCEL has extensive experience in close-range photogrammetry, and has developed an extensive and unique software package (CRISP) which can form the basis for the mapping system software. Modern analytical stereoplotters are well suited to the task of volume measurements from close-range photography, and this report will focus on the integration of an analytical plotter into a production mapping environment for ESP.

The scope of the study was to:

1) Verify hardware and software requirements.

2) Recommend equipment and procedures for underground stereo photography of 3-meter long segments of tunnel including left and right side-walls and ceiling.

3) Evaluate methods for digitizing data from stereo photography in the field. Digitizing must include fracture position and attitude (dip and strike), bedding attitude, and other linear features commonly measured in underground mapping.

4) Recommend work distribution between field office, home office and contractors. Recommend quality control and data editing procedures.

5) Recommend methods to link spatial fracture maps with other geoscientific data.

6) Evaluate methods for storage and retrieval of collected digital data. Examine 3-D data base concepts, vendors, etc.

DRAFT

7) Evaluate methods for interactive graphics data manipulation, and creation of hard-copy output in graphical and alphanumeric form.

8) Plan a high-throughput production chain.

This report will recommend procedures for data acquisition and analysis, based on the results of sample photography taken with a Hasselblad camera in G Tunnel, on the Nevada Test Site. During the site visit, discussions with the tunnel surveyors were initiated concerning control placement, and the camera positioning rig discussed in Section 3 was evaluated. The sample photographs were viewed in VEXCEL's Analytical Plotter, and recommendations developed for measurement and analysis procedures.

2.0 WHY PHOTOGRAMMETRY?

DRAFT

The use of close range photogrammetry for a mapping project such as the ESP offers many advantages over traditional manual methods.

1) Speed of primary image acquisition. Using the camera positioning device developed by George Fairer of the USGS, a 3 meter tunnel section can be photographed in less than 30 minutes.

2) Permanent Record. The films themselves provide a permanent record of the tunnel surfaces.

3) Multiple Use Imagery. Images can also be used for geologic interpretation, etc.

4) Separation of image acquisition and data collection tasks. The longer data collection process can be performed after images are obtained, resulting in greatly reduced time in the tunnel. Equally important, additional measurements can be obtained from the photos at any time, even years later.

5) Consistent level of accuracy throughout the project. Measurements can be repeated for quality control and consistency checking.

6) Collected data are in numerical format, suitable for loading to a database without manual coding.

7) Coordinates are three dimensional, and can be referenced to any coordinate system.

3.0 PHOTOGRAMMETRIC IMAGE ACQUSITION

DRAFT

3.1 Hardware

In order to compute the three dimensional coordinates of points on the tunnel faces, and the fracture positions and attitudes, stereo photography is required. This can be achieved using two cameras mounted in a fixed relationship, or a single camera which is moved a controlled distance between exposures. Because the objective is to cover an entire round of mining (≈ 3 meters) with stereo coverage in a single session, any setup (whether a single camera or a camera pair) would need to be moved. The only alternative would be a specialized panoramic camera which could scan the entire tunnel circumference. However, such cameras are not readily available, are expensive, and the imagery does not lend itself to conventional interpretation.

Recommendation 1 Conventional central perspective cameras should be used for image acquisition.

Rather than move a pair of stereo cameras, a specialized camera bar was designed by George Fairer of the USGS, which allows complete coverage of the tunnel segment using a single movable camera (Figure 1). The bar is a 3m long hollow aluminum tube which is supported at either end by a heavy duty camera tripod. A rotating and sliding camera mount is .ched to it. A single camera, attached to the mount, can be slid to one of three lateral positions which are determined by click stops on the bar. At each position, the camera can be rotated into 4 positions (Figure 2), 60° apart.

The lateral overlap of photographs must be 60% (50% is the minimum). The additional 10% serves as a safety margin, and also avoids the use of the extreme image edges. The rotational overlap should be approximately 20%. A detailed description of recommended camera procedures is contained in section 3.2.

DRAFT

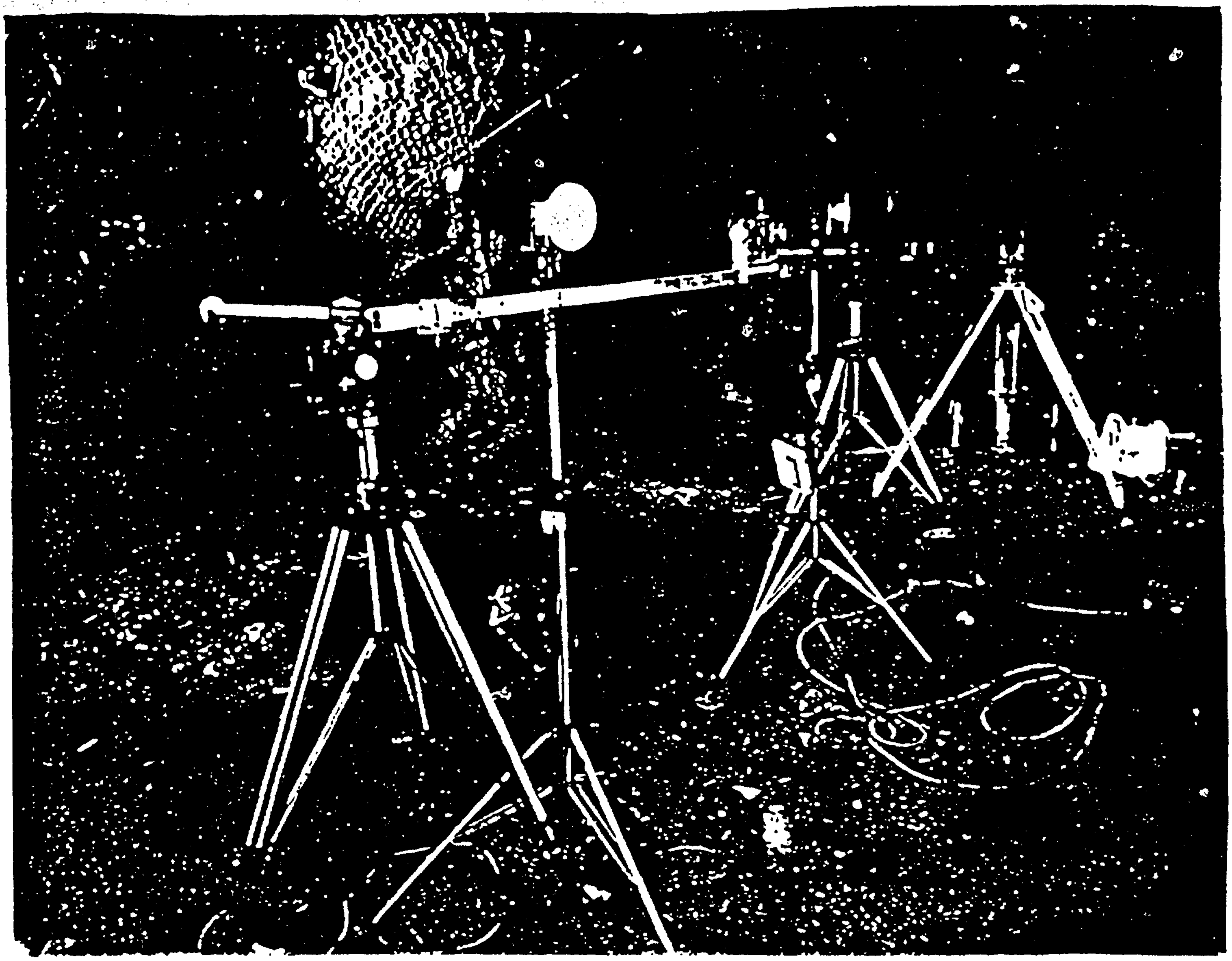


Figure 1 - Camera Positioning Rig

DRAFT

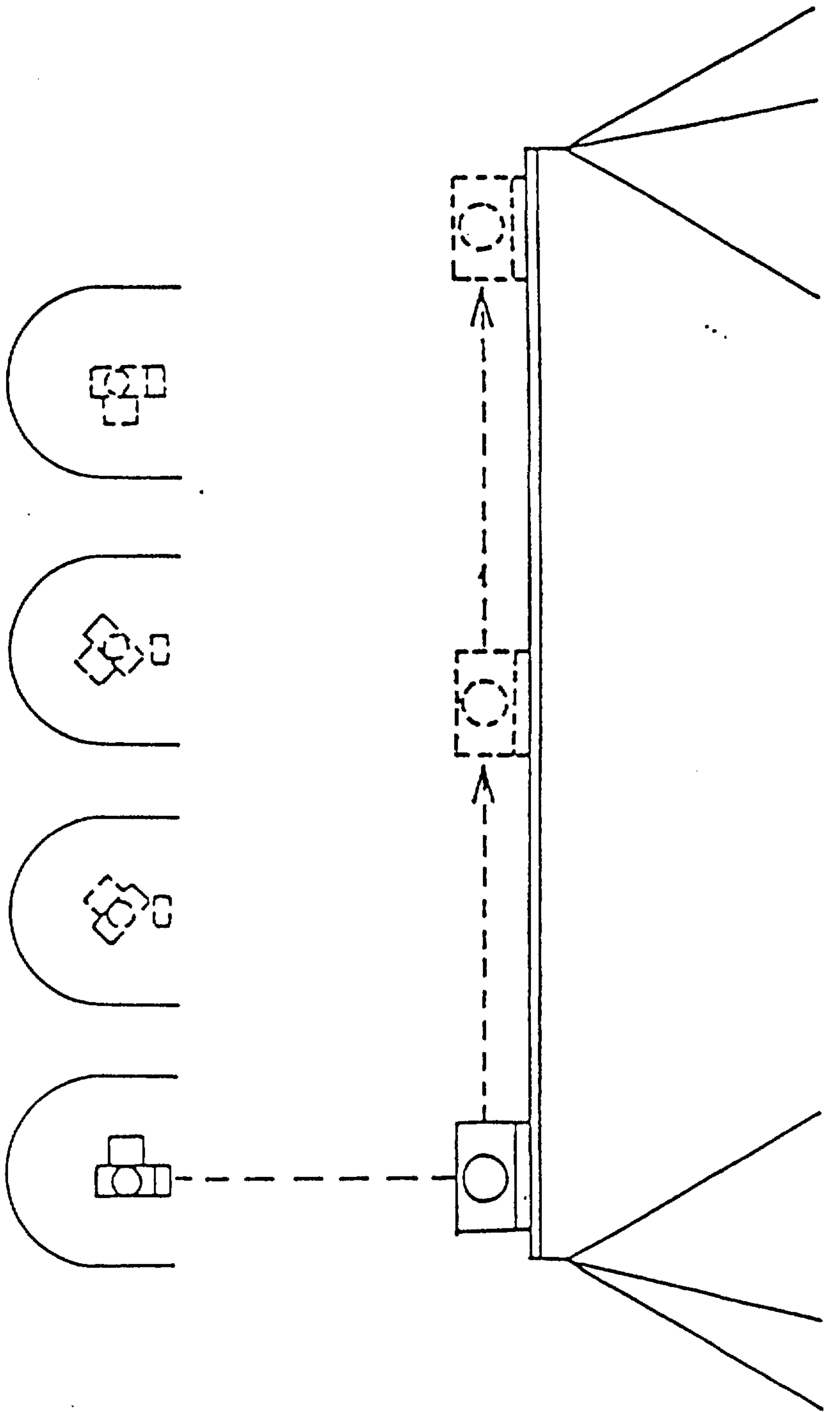


Figure 2 - Camera Orientations

There are many cameras available that could be used for the tunnel photography (Table 1). However, many of the precise photogrammetric cameras listed are rather cumbersome to use, especially for high volume photography in difficult conditions. Therefore, a non-metric 70mm roll film camera such as the Rollei SLX 6006 or the Hasselblad SWC/M is recommended. These cameras have the advantages of:

1) Relatively low cost
2) Ease of use
3) Can use roll film with motor drive
4) Polaroid film back available

The Rollei SLX 6006 is a new calibrated camera available from Rollei Fototechnic. It has a built in reseau plate with a series of 11 x 11 reference marks, and accepts Zeiss lenses from 40 to 500 mm. A data back will be available in the next month or so.

The Hasselblad cameras have a more complex data back/recording system available. However, they are more expensive than the Rollei camera, and do not have through the lens viewing.

The Rollei and Hasselblad cameras are described in more detail in Appendix A.

DRAFT

Table 1 - Close Range Camera Specifications

Manufacturer	Model	Film Format	Film Material	Depth of Field	Change Lenses ?
Hasselblad	MK70	6x6 cm	70mm Roll	•	Yes
Hasselblad	MKW	6x6 cm	70mm Roll	$0.9 \to \infty$	No
Jena	UMK 10/1318	13x18 cm	Glass Plates	$1.4 \to \infty$	No
Kelsh	K-470	10.5x12.7 cm	Glass Plates	$2 \to \infty$	No
Rollei	6006	6x6 cm	Roll Film	•	Yes
Wild	P32	6.5x9	Glass Plates	$0.6 \to \infty$	No
			Cut Film		
			Roll Film		

Although of high quality, these cameras are non-metric[1] and should be calibrated before use and at regular intervals during the project. Camera calibration consists of an analytical determination of the camera principal distance (focal length), principal point (intersection of the optic axis with the focal plane), and the lens distortion characteristics. It is performed by photographing a precise test field and analyzing the results with a camera calibration program. VEXCEL has this capability.

---

1. A metric camera is one in which the inner orientation parameters are known, stable, and reproducible. These parameters include the location of the perspective center, the focal length, and the location and orientation of the camera fixed-coordinate system. Some small cameras which include a reseau plate can be calibrated quite accurately, and the parameters computed. However, they cannot be considered stable, and must be re-calibrated at regular intervals

DRAFT

If the camera is to be used at varying focal settings or with different lenses, it should be calibrated in each instance. The calibration should be repeated at least every 6 months, depending on the level of usage of the instrument.

Once the camera is calibrated, the calibration parameters are used for all subsequent coordinate computations. Although the extremely high precision available from a calibrated camera may not always be required, without calibration no specific statement can be made concerning accuracies. Therefore, for quality control purposes alone, all cameras used in the project should be calibrated.

Camera calibration is more easily performed if the camera has a reseau plate installed. A reseau plate is a glass plate in the film plane with an accurately known pattern of grid marks on it. Without a reseau plate, the edges of the frame must be used for reference marks. This method is more difficult to use, more time consuming, and less accurate than methods employing a reseau plate. If frame edges are used, a series of points must be digitized along all frame edges in order to establish the frame corners, and hence the coordinate reference system. Reseau marks provide this reference directly and accurately. In addition, sub-sections of the frames can be measured, as long as 4 of the reseau marks are digitized each time. The reseau plate also serves to help with film flattening (a major source of error) as well as with the calibration.

If the camera is available in a pre-calibrated form, it is probably cheaper to purchase it that way. For future calibrations, a test field should be constructed. The test field must consist of accurately known targets arranged in a pattern that provides complete X and Y coverage of the camera field of view, and sufficient depth of field (Z) to allow accurate determination of the camera focal length. Rigorous camera calibration software is required to determine principal distance (focal length), principal point location, and lens distortion coefficients.

Recommendation 2 (Camera)

a. Should use standard 120, 220, or 70 mm roll film

b. Rollei 6006, Hasselblad SWC/M, or Hasselblad MKW

c. Must be calibrated at regular intervals (<6 months or whenever settings changed)

d. Should have reseau plate installed

e. Should take Polaroid Film Back

f. Should have data back available

The Rollei SLX 6006 camera is recommended above the others. It is the latest design, comes accurately calibrated, and has demonstrated high precision in various tests.

3.2 Image Acquisition Procedures

The main goal of the image acquisition phase is to completely and quickly acquire stereo photographic coverage of a tunnel section. The longer the photography takes, the longer the mining operations are delayed. Therefore, the following procedures are suggested.

1) The camera bar setup should be placed in position as quickly as possible, using the laser theodolite for centering and measuring purposes (see section 3.3). An accurate setup of the camera will reduce the amount of survey control required and will improve measurement accuracies.

2) After alignment of the bar, the survey control points should be established and measured, using a right-angle moveable prism on the bar (see section 3.3).

3) During the setup phase, the camera should be loaded with film and checked. Lighting should be setup and adjusted. The lens should be cleaned and focal setting and f stop verified. A small f stop such as $f/16$ or $f/22$ should be used because the

central portion of the lens contains less distortion. The cameras must always be used at the same focal setting, which should allow sufficient depth of field to ensure that all features are in sharp focus.

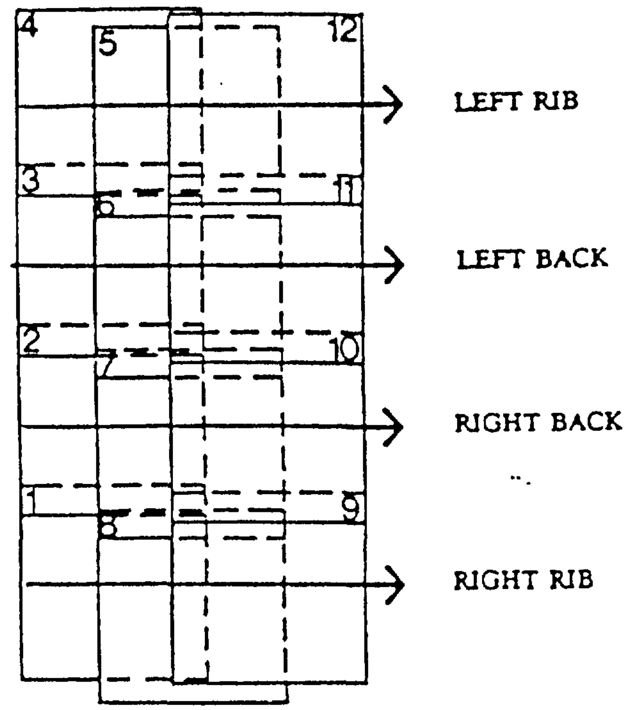
4) After setup is completed, the photographs should be exposed in a systematic fashion, with 4 photos required at each lateral camera position in order to cover the ribs and back of the tunnel (see Figure 3).

5) Each photograph should be identified on the negative with a systematic numbering scheme. If possible, an electronic data back with alphanumeric data display should be used. Otherwise, a small "story board" should be placed in the field of view, and a unique number placed on it for each frame.

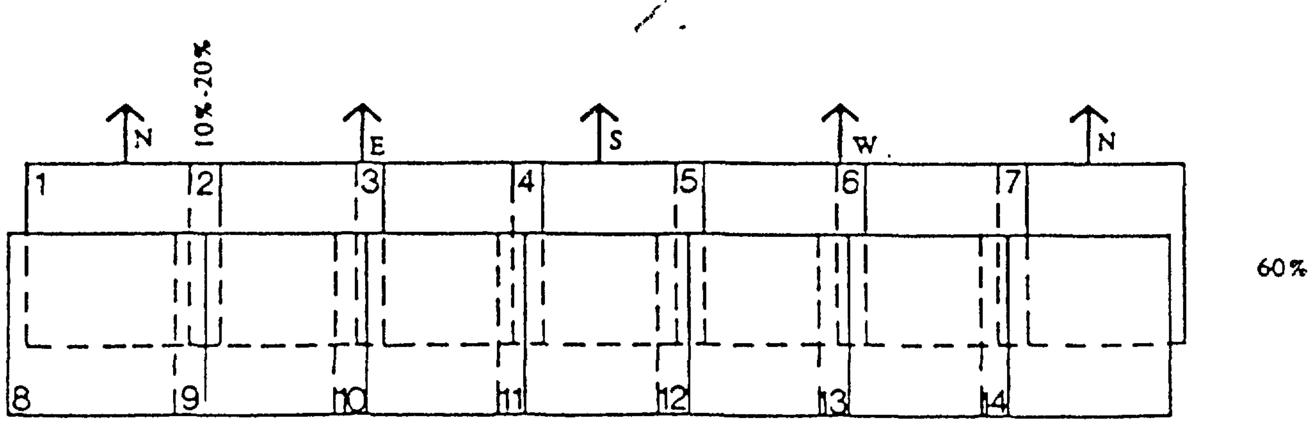
6) During photography of the vertical shaft, the camera will be supported on a platform that can be lowered down the shaft. The camera will be located on a tripod near the center of the shaft, and rotated between exposures to achieve complete coverage. Rotational overlap should be between 10% and 20%. The tripod should then be lowered a sufficient distance so that the second round of photographs has a 60% overlap with the first.

In order to achieve reasonable photogrammetric measurement accuracy from the photographs, a suitable Base to Height (B/H) ratio is required, where the base is the lateral distance between camera positions and the height is the distance of the camera from the surface being photographed. If a 40 mm lens is used, the coverage of a single photograph will be approximately 2.75 m x 2.75 m, assuming a drift radius of approximately 2 m. The camera will be moved approximately 1.1m between exposures, resulting in a satisfactory B/H ratio of approximately 0.55. Similar conditions can be achieved for shaft coverage.

DRAFT



(a) Tunnel Layout



(b) Shaft Layout

Figure 3 - Photo Layout

DRAFT

In theory, careful positioning of the camera for each exposure is not required, as its orientation can be computed photogrammetrically. However, in practice there are several reasons to position the camera in a systematic fashion:

1) Complete coverage is assured - no overlaps or gaps.

2) Should there be a problem with the surveyed control points, the camera position data will still allow data collection.

3) All photos along, for example, the right rib have the same orientation. Photo mosaics can be easily constructed, and the task of photo interpretation is eased.

4) As experience is gained, it may be possible to greatly reduce control requirements.

Recommendation 3 The camera should be systematically and carefully positioned for each exposure.

After films are exposed, they should be labeled and stored in a protected environment. During transportation to the film processing site, they should be protected from extremes of temperature and humidity. Rapid changes may affect film dimensional stability and subsequent measurement accuracy.

3.3 Survey Control

DRAFT

Many different coordinate systems are involved in a project such as this. When the photographs are measured in the Analytical Plotter, image coordinates are produced. They are in a coordinate frame of reference defined by the reseau plate. When two overlapping photographs are oriented with respect to each other to form a stereo model (see Section 4), the coordinates thus measured are called model coordinates. They are three dimensional, but in an arbitrary frame of reference and with arbitrary scale.

Survey control markers are required for absolute orientation of the photogrammetric models. Absolute orientations means the scaling, leveling, and orientation to ground control of a model or group of models. These markers have known X,Y, and Z coordinates in any unified coordinate system such as Latitude, Longitude and Height (Geographic), or as Northing, Easting and Height (UTM or State Plane Coordinates). They should be well defined targets fastened securely to the shaft or drift surface in a predefined pattern.

In the simplest case, the pattern could be such that 3 control markers would appear in each stereo model (pair of overlapping photos). This would allow independent setting up of each model without any photogrammetric adjustment procedures. However, each round of photography (12 photos in the horizontal tunnel) results in 9 models, so 27 survey control points would be needed. If the survey points were accurately placed in the model overlap areas, point sharing would reduce this number to 14.

At the other extreme, a few points could be scattered along the ribs and the back, perhaps one marker per 25m or so. However, a large "block adjustment" would be required to tie all the images together and to provide a computed absolute orientation.

DRAFT

A block adjustment is a numerical method for orienting a group of photos or models with respect to each other, and also with respect to the ground coordinate system. A block is usually considered to be a group of photos in rows and columns, while a single row of images is called a strip. The larger the block, the longer the computation time. During computation, the Analytical Plotter is blocked from other tasks.

The present survey methods in G Tunnel are based on the use of a laser theodolite. Once an accurate centerline is established, the laser can be used to position and measure the location of the camera bar. In addition, if a right angled prism is mounted on the bar, the laser can be used to position and measure points on the tunnel surface.

Assuming that control points can be established and measured rapidly using the right angled prism on the camera bar, approximately 10 points would be sufficient, as shown in Figure 4. This will provide sufficient control to easily adjust individual strips, or the entire block, yet will be faster than establishing full control. Note that some of these control points can be used in the next round, reducing the overall control requirements.

It might be possible to greatly reduce the control requirements. If the camera can be located with sufficient accuracy (both in X,Y, and Z position <u>and</u> orientation), the control point count could be reduced. However, the number required should be determined by experiment. The following procedure is proposed:

1) A new set of photographs should be taken in G Tunnel, using the calibrated Rollei camera.
2) A full set of control should be established for one round.

DRAFT

3) The camera should be accurately located and the location parameters recorded.

4) The photographs should be set on the DSR-11 with varying control configurations.

5) A table of accuracy vs control should be computed.

These photographs could also be used for the mapping verification study proposed in Section 4.

Note that the time spent establishing control in the drifts cannot be directly correlated to the model set-up time. This item is discussed further in Section 4.

The points must be located in the overlap areas of the photographs in order to tie the strips together. This should not be difficult, given the controlled camera setup and the prism method of control establishment. Survey point coordinates should be measured and computed more accurately than the required accuracy of the final result. Although extreme precision may not be required immediately, there would be no way to increase measurement precision in the future if precise survey coordinates are not available.

Recommendation 4 (Survey Control)

a) Survey control markers should be well defined and securely attached targets.

b) They should be accurately surveyed to an accuracy greater than the required final results.

c) They should be established in a systematic fashion.

d) A further test should be undertaken to determine minimum control requirements.

DRAFT

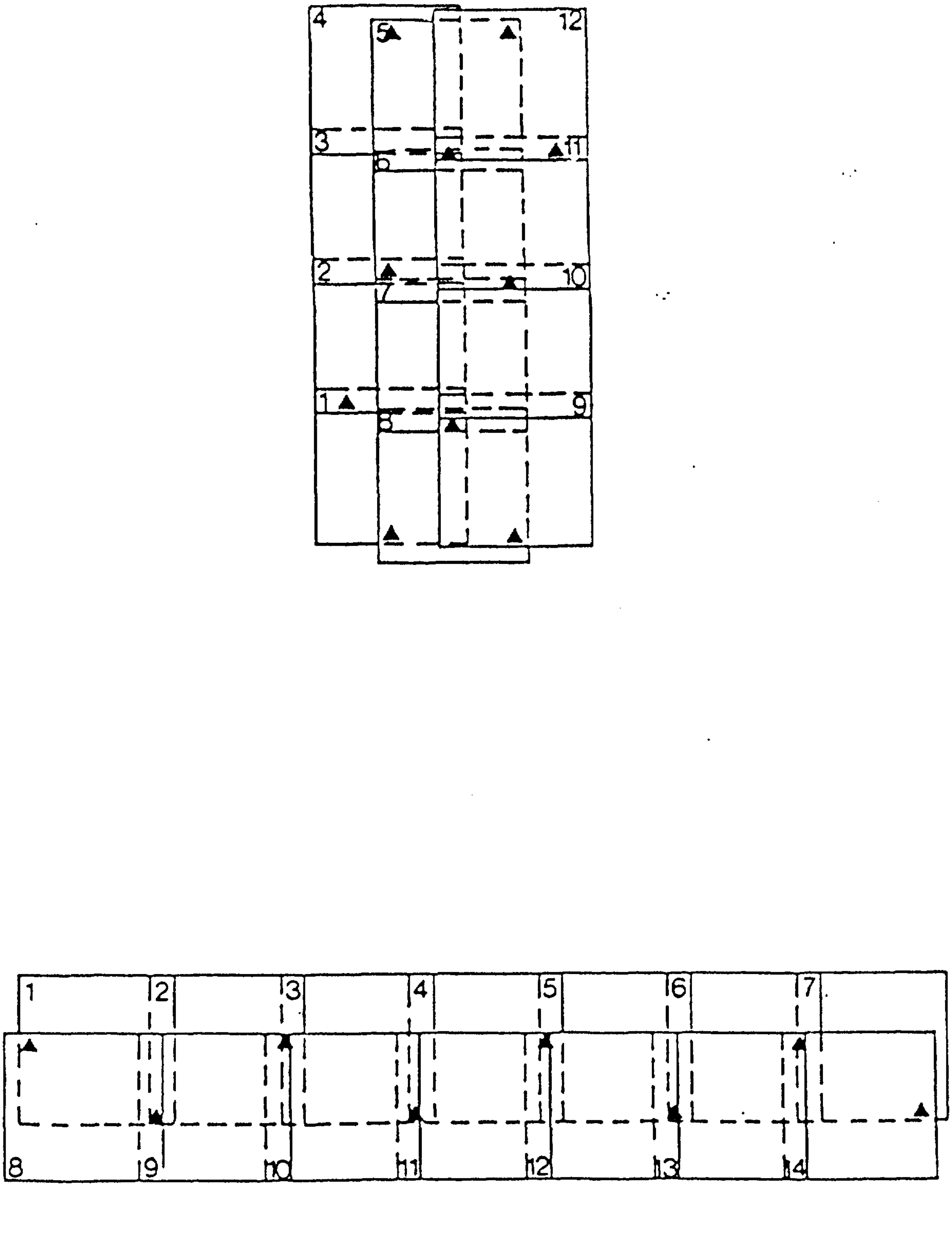


Figure 4 - Control Arrangement

4.0 PHOTOGRAMMETRIC DATA COLLECTION

DRAFT

4.1 Photogrammetric Hardware

Once stereo images of a tunnel or shaft segment have been acquired, processed, and labelled, they must be measured in order to obtain 3D coordinate values for the items of interest (which can be anything visible in the photographs). An analytical stereoplotter is a computer-driven opto-mechanical device specifically designed for precision stereo measurements of photographs taken with a wide range of cameras. Classical analog stereoplotters do not lend themselves to the task since they do not permit one to work efficiently with close range non-metric photography.

Although there exists five major brands of Analytical Plotters (Wild, Zeiss, Kern, Integraph, Matra) we propose to focus on the Kern DSR-11 Analytical Plotter, manufactured by Kern Instruments of Aarau, Switzerland. Its specifications are shown in Table 2. The Kern instrument has several advantages for the ESP work:

1) Availability of the CRISP close-range software package (see Section 4.2). Analytical plotters are completely dependent on software, and this package would provide the basis for a Geological Measuring Package. There is no equivalent package for the other instruments.

2) Availability of custom software support. VEXCEL has a Kern DSR-11 in Boulder, running the CRISP package, and can provide training and support.

3) Widespread use of Kern instruments in the United States.

4) The Technical Institute in Denmark has a geological package running on a DSR-11.

DRAFT

Table 2 Kern Specifications

Approximate Size	1.5 x 1.5 x 1.5 metres
Stage Size	25 x 25 cm
Processors	PDP 11/73, 11/23
Disk Capacity	30 - 70 MBytes
Optical Resolution	68 line pairs/mm
Magnification Range	5 - 20 x
Optical Adjustments	Floating Dot Size, Illumination
	Individual Stage Illumination
	Squint Adjustment
	Image Rotation
Measuring Resolution	1μ m
Measuring Accuracy	$\pm$ 3μ m before calibration

GPI Plotter

Table Size	1400 mm x 1200 mm
Inclination of Working Surface	0° - 60°
Resolution	40μ m
Repeatibility	40μ m
Max Plotting Speed	370 mm/sec
Acceleration	6m/sec^2

DRAFT

One of the other analytical plotters could be substituted, but a major effort of software conversion would be required. The Kern DSR-11 contains an optical train for stereo viewing of negatives and diapositives, moveable stages for image mounting, and 2 DEC PDP/11 computers for process control. The instrument can be coupled to a variety of output graphics plotters. Kern manufactures the GP-1 flatbed plotter, but also integrates 3rd party hardware with the DSR/11 (Datatech, Houston Instruments, etc.) Both the DSR/11 and GP1 are further described In Appendix B.

The basic Kern software is designed for traditional aerial mapoing. However, VEXCEL sells and supports the CRISP software package, specifically designed for close-range photogrammetry (Appendix C). CRISP allows the user of the DSR-11 to work with metric or non-metric camera photography (calibrated or non-calibrated), in the form of single images, single stereomodels, and blocks of images. CRISP also has a set of utilities for performing application specific measuring tasks. As discussed in Section 4.2, additional utilities can be developed to aid in the ESP geological mapping. It is relevant to point out that no other commercially available software package currently exists for Analytcial Plotters that can process such a range of metric and non-metric photography. VEXCEL distributes, maintains, and modifies CRISP in the United States.

The Kern hardware should be located in a relatively dust free, vibration free environment for best results. It should be cleaned on a regular basis, and protected from temperature extremes.

The instrument should be calibrated on a regular basis. A grid plate and calibration program are supplied by Kern, and the entire calibration procedure takes less than an hour. The calibration results are stored in a file on the system, and corrections are applied automatically to all subsequent measurements. The calibration procedure can be done by the DSR-11 operator.

Kern also supplies an option that superimposes the collected data over the image, in the optical train of the Analytical Plotter. This allows the operator to monitor data collection without having to remove his or her eyes from the eyepieces.

Recommendation 5 Analytical Plotter Hardware

a) A Kern DSR-11 Analytical Plotter should be used for image measurement and coordinate computation.

b) Any suitable flat bed or drum plotter should be used for data plotting.

c) The DSR-11 should be calibrated at regular intervals (<2 months).

d) The hardware should be located in a stable air-conditioned environment.

e) The use of image superimposition should be investigated.

4.2 Photogrammetric Software

The CRISP software system provides the framework for all data collection and analysis tasks. The work flow would be as follows:

i) Project Definition. All project parameters are input into files. Cameras are defined and camera calibration parameters stored. This need only be done once at the beginning, and as cameras change.

ii) Inner Orientation. The images are placed on the plate carriers and the fiducial marks digitized. Fiducial marks are index markes rigidly connected with the camera lens through the camera body and which form images on the negative. Reseau marks can be used for this purpose. CRISP drives to each fiducial mark after the first has been measured. If the camera has no fiducial marks, image corners must be used. This is not recommended.

iii) Relative Orientation. The two members of the image pair are oriented with respect to each other to produce a stereo model.

iv) Control Point Measurement. All control points visible in the model are digitized.

v) Feature Measurement. All fault lines, fractures, planes etc. are measured and stored.

This process (ii-v) is repeated for all models in the group of images being processed. Generally, this would be 8 models, covering 3 metres of tunnel. Then an adjustment would be performed to tie all the models together in the world coordinate system. All measured features would also be automatically transformed into the same coordinate system. Residuals on the control points would be given, allowing the operator to remeasure control points as needed.

Once an adjustment has been performed, any model in the group could be reset at any time in a matter of minutes, and additional measurements made in the world coordinate system. No readjustment is required. Thus, features could be added at any time.

However, this method has this disadvantage that plotting in the world coordinate system would be delayed until after all models in a round had been processed. An alternative method would be to perform the <u>orientation</u> of all models initially. If a block adjustment method were being used, then all control points would be measured in all models, the adjustment performed, and then the models reset for feature measurement and plotting in the world coordinate system. Both these methods should be tested to determine the time required for model set-up.

Measurements are performed by tracing features or locating points with a "floating mark" visible in the DSR optics. Handwheels or a freehand motion can be used to move through the model, and a footswitch or handswitch used to actually digitize a point. The system can also operate in stream mode for digitizing linear features.

CRISP does not currently have specific utilities for digitizing geological features and computing strike and dip. Some customizing of existing software would be required in order to have a production environment suited for the tunnel mapping. Such an effort would require careful specification of utilities on the part of the USGS. Approximate levels of effort that might be involved are discussed in Section 6. It might be possible to integrate the Geo package developed by Keld Duholm of the Geological Survey of Denmark, into CRISP. However, VEXCEL has not evaluated this package at this time.

Once the data are digitized and transformed, they need to be stored in a data base. This issue is discussed in more detail in Section 5. However, during the digitizing phase, some operator input will be required to identify features being mapped. This might consist of only a sequence number, or a longer alphanumeric identifier. Input would be from the Kern terminal keyboard. The use of the image superimposition system would speed data collection, because the operator would not need to turn from the instrument to minitor progress.

4.3 Work Load

In view of the large number of photographs that would be encountered in a production situation, careful workload planning would be required to ensure timely production of measurements from the tunnel photographs. The following discussion is based upon a number of assumptions, and is approximate in nature, but indicates the general magnitude of the work load that might be expected.

DRAFT

Assuming that, in a 4 metre diameter drift, two 3 metre rounds were completed per 24 hours, with approximately 8 models (12 photos) per round, then 16 models per drift/tunnel per 24 hour period would require processing. If the vertical shaft mining were proceeding simultaneously, with 10 models per round, and one round per 24 hours, then another 10 models per 24 hours would require processing.

The Analytical Plotter could be operated in 3 shifts, 24 hours per day. Nominally, 2 people per shift might be required - one to perform the measurements and one to provide support activities such as image preparation, file organization, plot checking, etc. Assuming that the second person could prepare all images and control data, it might take up to 2 hours per model to perform all measurements and computations. However, this number is <u>very</u> dependent on the level of detail that is to be acquired from the photographs. It could at the lower end of the range if only an initial coarse level of mapping is to be performed.

Even assuming one hour per model, the 16 models from the tunnel and 10 models from the shaft would overload the capacity of a single DSR-11. If two tunnels were being mined simultaneously, then 2 DSR's would certainly be needed. Time must be allowed for the photo adjustments, quality control, and maintenance.

Other alternatives could include:

1) Off-line measurements of some models on a comparator type machine. However this would be slower, require additional software to interface the measured data to the Analytical Plotter, and would be less convenient.

2) Measurement of only one portion of the tunnel, for example the left or right rib. This would cut the volume of models to about one third of the entire tunnel, and might allow simultaneous processing of the images from one tunnel and one shaft on a single instrument.

Some time is required for quality control and data editing. On line checking can be performed by simultaneous plotting of the mapped features on the graphics plotter. Plotting software would be required to produce usable hard copy output of the three dimensional tunnel and shaft surfaces. As each model was mapped, the operator could easily verify linear feature connections at the model boundaries. After model plotting was completed, a quality control supervisor should review all diapositives and plots to ensure consistency and coverage. During plotting, spot checks should be performed to verify positional accuracy of random features. Occasionally, an entire model should be reset and remapped. Data editing is discussed in Section 5. A proposal for a more complete analysis of mapping times is presented in Section 4.4.

The physical location of the Analytical Plotter will depend on a number of factors. For example, its location in Denver would increase the time required for receipt of films from the tunnel site, and return of data. However, the operating environment would be more protected, and service and maintenance would be more easily obtained. The physical location of the data base is not important, as remote access can easily be arranged. A reasonable compromise might be the location of the mapping centre in Denver, with a high data rate link to the tunnel site so that hardcopy plots, data and graphic displays could be downloaded as needed in the field.

However, the field office should definitely be responsible for all image acquisition, processing, labeling, and organization. Only a duplicate set of images should be sent to the home office for mapping purposes. The use of a reseau camera enables the Kern to remove all distortions resulting from the duplication process.

A training program will be required to educate both the Analytical Plotter operators and the users of the plots and various data base products. The content of this program will depend on the scope of the mapping effort. A framework for ongoing training and system upgrading must be developed.

Recommendation 6 Work Flow

DRAFT

a) Analytical Plotter should be operated on three 8 hour shifts.

b) Two people required per shift, or three for two instruments.

c) Quality control supervisor should check all plotted output.

d) Random checks should be made on coordinate accuracies.

e) If the Analytical Plotter is located in Denver, high speed data links should be established to the field office.

f) A training program should be developed.

4.4 Preliminary Testing

A set of test photographs from G Tunnel were delivered to VEXCEL. A minimum amount of control had been targeted and surveyed prior to photography. A small block adjustment was performed, and several models set on the Kern DSR-11. Due to the control arrangement, a full study of mapping time and accuracy could not be performed. Therefore, an additional test is proposed. However, the following items were apparent:

1) The quality of photography is good. Color, lighting, and resolution are satisfactory.

2) Geological features can be seen and mapped from the photographs.

3) Model set-up was straightforward.

DRAFT

4) It was not possible to test the effects of reducing control, as only a minimum amount of control was available.

5) A further test should be performed comparing photogrammetric and manual measurement of features on a test segment of drift.

A simulation of expected accuracy was performed (Tables 3 and 4). Note, however, that those results should be verified experimentally, preferably from a new set of photographs taken with a calibrated camera. Table 3 shows the simulated errors in measured X,Y and Z coordinates, given the assumptions listed in the table. Table 4 gives approximate errors in computed attitudes of planes, given the X,Y,Z errors from the first table, for both calibrated and uncalibrated cameras.

As discussed previously, several additional tests need to be performed:

1) A comprehensive test of survey control requirements (see Section 3.3).
2) A test of model set up and mapping times.
3) A comprehensive test of actual feature mapping. The area covered by several models should be mapped manually by 2 or 3 people, and photogrammetrically by 2 or 3 people. The resulting plots should be overlaid and compared. In addition, test computations of strike and dip should be performed. An estimate on the percentage of fractures that are difficult to measure using each method should be computed. Section 6 gives an estimate of the effort required to perform these additional tests.

During this testing procedure, VEXCEL and the USGS should develop a well-defined list of software modifications that would be required for CRISP.

4.5 Other Applications

The Kern/CRISP combination could also be used for other mapping purposes, a few of which are listed here:

1) General site mapping. Aerial photography of the overall storage site could be used for updating site maps.

2) Surface roughness profiles. Close range stereopairs could be taken of various surface features. If diapositives of a scale of 1:10 were available, profile height accuracies on the order of 0.05 to 0.10 mm could be achieved. A dense system of profiles could be quickly generated, because the DSR-11 can drive automatically across the surface, leaving the operator only to raise and lower the measuring mark.

3) Deformation monitoring. Tunnel surfaces can be monitored by photographing at regular intervals.

DRAFT

	Error in Image Coords	Error in Relative X,Y Coords	Error in Relative Z Coords
Calibrated	10 μm	± 0.35 mm	± 1.3 mm
Uncalibrated	50 μm	± 1.8 mm	± 6.5 mm

Assumptions

"Vertical" Photography (Parallel to one rib)

B/H = 0.55

Object Distance = 2 m = H

focal length (f) = 40 mm

Z axis is into drift wall

$$\sigma_x = \sigma_y = \frac{H\sigma}{\sqrt{2}\, f}$$

$$\sigma_z = \frac{\sqrt{2}\,\sigma H}{(B/H) f}$$

Table 3 - Errors in X,Y,Z Coordinates

DRAFT

Approximate Error in Attitude of Plane

Angle to Camera Axis		Plane Dimension 2m x 2m	1m x 1m	0.5m x 0.5m	0.25m x 0.25m	0.1m x 0.1m
90°	Cal	4'	8'	16'	32'	1° 20'
	Uncal	22'	44'	1° 28	2° 576	7° 20'
60°	Cal	5'	10'	20'	40'	1° 40'
	Uncal	35'	1° 10'	2° 20'	4° 40'	11° 40'
45°	Cal	9'	18'	36'	1° 12'	3°
	Uncal	44'	1° 28'	2° 56'	5° 52'	14° 40
30°	Cal	12'	24'	48'	1° 36'	4°
	Uncal	1°	2°	4°	8°	20°

Table 4 - Errors in Plane Attitude

DRAFT

5.0 DATA BASE DESIGN AND IMPLEMENTATION

The data base design is critical to the success of the tunnel mapping project. The data base system must be able to handle large volumes of data, provide fast response times, include an efficient user interface, and provide graphical and tabular output capabilities.

A database is defined as a collection of stored operational data used by the application systems of some particular enterprise. In general, there will be associations or relationships linking the basic data groups together.

The implementation of a proper database system provides the following advantages:

1) The amount of redundancy in the stored data can be reduced.

2) Problems of inconsistency in the stored data can be avoided.

3) The stored data can be shared.

4) Standards can be enforced.

5) Security restrictions can be applied.

6) Data integrity can be maintained.

DRAFT

Data systems can be grouped into three main categories, based on the data model supported by the system:

1) Relational
2) Hierarchial
3) Network

The relational data model has several advantages over the others, and is found in many current commercial database systems. A theoretical discussion of the relational data model is beyond the scope of this report, but in general one can think of the data as being stored in "highly disciplined" files, or relations. Each file contains only one record type, which has a fixed number of fields. Each record occurrence has a unique identifier, and either an unknown ordering or an ordering according to values contained within those occurrences.

The data digitized on the Analytical Plotter will have the format of [FEATURE ID, $X_1Y_1Z_1$, $X_2Y_2Z_2$, ...] where there may only be a single [XYZ] for a point, and multiple coordinates for linear features. The feature ID can serve as a link or key to an attributes database, where feature descriptions are stored. In relational database terminology, all the coordinate data would be stored in one relation and the attribute data in another. Attribute data might include strike and dip, rock type, etc, etc. Other relations could store global site data, and other geoscientific data.

In reality, there are many other constraints on the data construction. All relations must be "normalized" in order to remove any possible functional dependence among relations. A relation in so-called fourth normal form (4NF) is one for which each of the underlying data domains contains atomic values only. Again, a formal discussion of normalization is beyond the scope of this report. However, care must be taken to avoid dangerous data dependencies in the database.

DRAFT

The Data Base Administrator (DBA) should carefully define all relations and data domains and attributes. Particular care should be given to which values will be keys in the relation, and which data storage methods will be used (ISAM, hashed, heap, etc.).

In the ESP database, data will be frequently retrieved on the basis of XY and Z coordinate values. For example, a user may wish to see a graphic representation of all fractures longer than 20 cm on the right rib of Tunnel 2 between stations 11+20.00 and 15+30.00. The system must be able to translate requests of this nature into queries on the XYZ database, select the items of interest from the database, and present them in graphical format. Most likely, a front end program will be required to generate the queries, and a back end program to perform the graphics operations.

Other queries might consist of searches for all fractures above a certain Z coordinate, located in a certain rock type, which have a certain strike and dip. Queries of this nature should be entered in a "forms oriented" query system, where the user can build up queries on a screen, edit them, then submit them for processing.

The INGRES data base system developed and marketed by Relational Technology Incorporated of Alameda, CA, is one of the best examples of modern relational database systems. It runs on a variety of hardware (VAX, μVAX, IBM Mainframes, etc), and can download data to an IBM PC/XT/AT. It has a visual forms editor. Promotional forms on INGRES are contained in Appendix D.

Data loading could be done directly from the Analytical Plotter. A utility program on the Analytical Plotter could format the collected data into INGRES input files, and transmit them to, for example, a μVAX running INGRES. There they could be uploaded to the database automatically. In addition, other utilities running on the μVAX could be used to upload other geologic data of interest. The 3D coordinate system would serve to reference <u>all</u> data in the database, including surficial geology data.

DRAFT

INGRES also supports a distributed database. An IBM PC/AT operating in the field could access a database in Denver, download data, and manipulate it locally. Full database integrity is maintained during remote operations. The remote data could then be displayed graphically. Figure 5 is an example of how this approach would work. Some software development would be required, especially for the graphic output. Hardcopy tabular reports can be generated by existing INGRES utilities, and could be printed on a local printer. The database could be accessed simultaneously by many users in different geographic locations, thus increasing its utility.

Another possible database system is produced by Intergraph. This is a VAX based system which combines data input, editing, and storage and retrieval software. Data can be easily downloaded from the Analytical Plotter and converted to Intergraph format. Intergraph implements a full Geographical Information System (GIS). Attribute tables can be generated for all entities in the database, and data can be easily viewed and edited at high resolution graphics workstations (see Appendix E).

Intergraph has the advantage of offering a more integrated data editing and manipulation environment. However, it is less flexible than INGRES as a database system, and is more expensive.

However, in a Analytical Plotter/INGRES environment, a separate data editing capability would be required. One alternative is MAPS 300 from AP, a map editing system that runs on then AP and interfaces to the CRISP software. Another alternative would be Autocad, a PC based CAD system that is quite flexible and powerful. However, some interface routines would be required to load the AP data into an AT running Autocad. A third alternative is the KORK software package, which allows online data editing and manipulation.

Any data editing environment must include the ability to interactively add, delete and modify points and lines, to scroll over large mapping areas, and to zoom into areas of interest

DRAFT

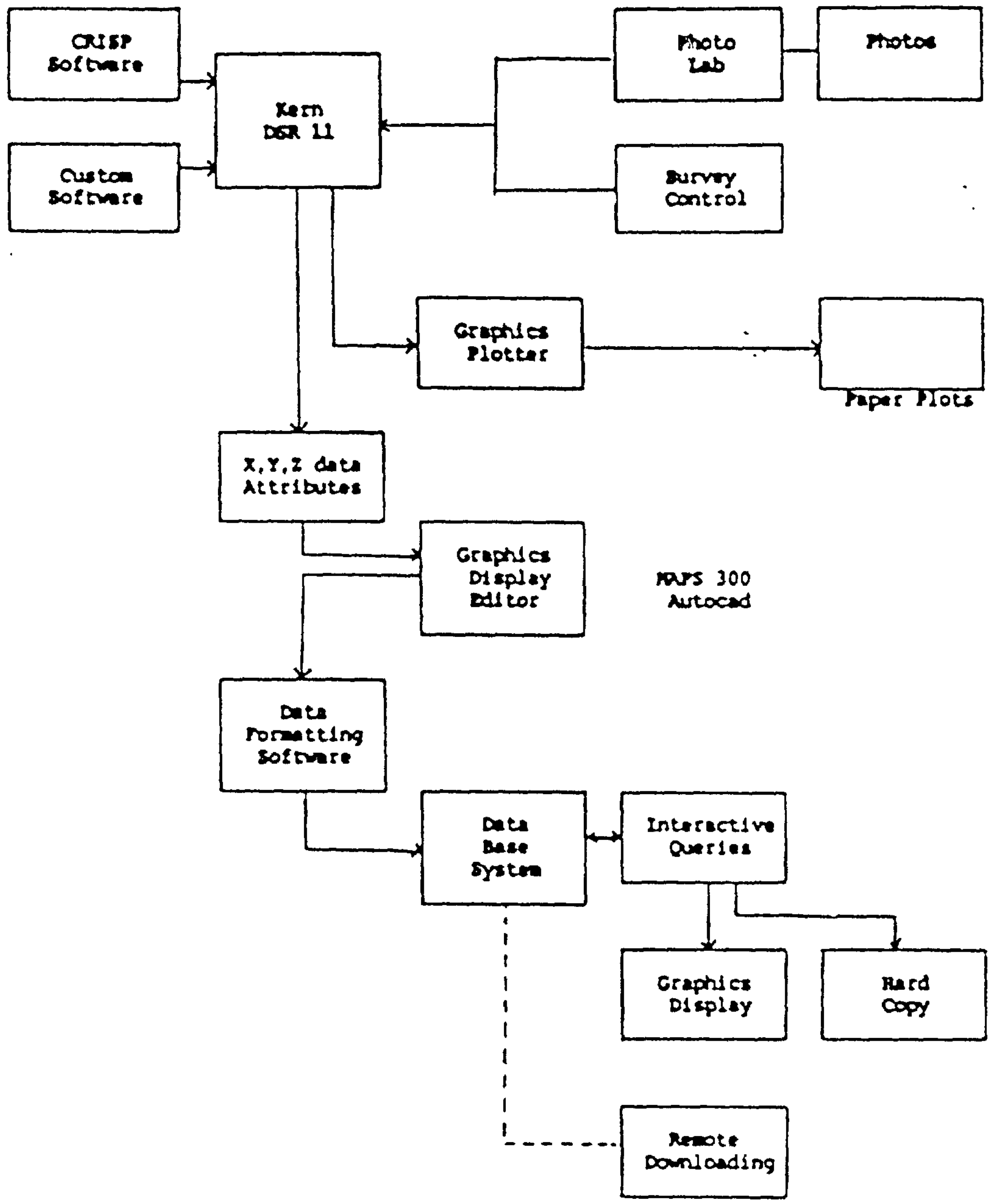


Figure 5 - Data Flow

DRAFT

Recommendation 7 - Database

1) A relational data model should be employed.

2) A Data Base Administrator should define all data requirements.

3) All relations must be in 4NF.

4) The INGRES database system should be evaluated more closely.

5) A fully distributed system should be implemented.

6) Utilities should be developed to upload data from the Kern directly.

7) Utilities should be developed for remote graphics display.

6.0 PROPOSALS

Three proposals for possible system configurations are included here for discussion. The represent three different orders of magnitude in system complexity, capability, and overall cost. All costs are approximate, but do serve as reasonable estimates. Many other configurations would be possible. In addition, an estimate of costs for the additional testing outlined in Section 4.4 is presented.

6.1 Full Scale System

A full scale system would include calibrated cameras, an Analytical Plotter with graphics plotter and CRISP software, and a database/data editing system. It would include the capability to collect large volumes of data, easily edit them, and would contain remote data analysis facilities.

	Analytical Plotter	$ 125 K	
	Graphics Plotter	$ 10K - 40K	
	PDP Computer	$ 15 K	
	CRISP	$ 20 K	
	VEXCEL Custom Software	$ 60 K	(Six month effort)
	Software Support + Consulting	$ 10 K/year	
	Rollei 6006 Camera	$ 15 K calibrated, reseau	
or	Hasselblad SWC/M	$ 3-4 K uncalibrated, no reseau	
or	Hasselblad MKW	$ 20 K calibrated, reseau	
	VAX Ingres	$ 40 K (VAX not included)	
	Custom Software	$ 20 K	
	Photogrammetric Map Editing System	$ 16 K	

DRAFT

or IBM PC/AT w Autocad	$ 8 K	
Custom Software	$ 10 K	
Remote Systems	$ 10-$20 K	
Integraph System	$ 300 +K (Includes VAX)	

6.2 Intermediate System

This system could serve as a full database system with more limited capability. Some flexibility in data entry and editing would be lost. The database would be maintained on an AT rather than a VAX, limiting the overall data volume, and slowing response time. Data collection capabilities would remain the same. Therefore, the database could be reloaded into a larger environment sometime in the future as needs grow.

Analytical Plotter	$ 125 K	
Graphics Plotter	$ 10 - 40 K	
PDP Computer	$ 15 K	
CRISP	$ 20 K	
VEXCEL Custom Software	$ 40 K	(4 month effort)
Software Support	$ 8 K/year	
Rollei 6006	$ 15 K	
IBM PC/AT with Autocad	$ 8 K	
Revelation database (runs on AT)	$ 2 K	
Custom Software	$ 20 K	

DRAFT

6.3 Evaluation System

The data would be collected on a Kern DSR-11 located at VEXCEL. Existing CRISP software would be used, but some modifications would still be required for geological mapping. Collected data would be edited at VEXCEL, and downloaded to a database system at the USGS, running on an AT. This system would serve to evaluate the functionality of the photogrammetric tunnel mapping system.

Use of Kern DSR-11 - +GPI + CRISP	$ 36.50/hour
Operator	$ 20.00/hour
Modifications to CRISP -	$ 20 K
IBM PC/AT running Autocad + Revelation	$ 10 K
Custom PC Software	$ 20 K
Rollei 6006	$ 15 K

DRAFT

6.4 Proposed Additional Testing

1)	New photography using calibrated camera	2 day site visit $1,500
2)	Models set on Kern with varying control configurations	3 days Kern $1,350
3)	Timing of various model set ups	1 day Kern $1500
4)	Test plotting of drift section by 2 or 3 operators	15 days Kern $7500
5.	Misc	1 day $ 750
	Total	$12,600